132901
132901

(NASA-CR-132901) FEASIBILITY MODEL OF A HIGH RELIABILITY FIVE-YEAR TAPE TRANSPORT, VOLUME 1 Final Technical Report, 5 Jan. 1972-5 Nov. 1973 (IIT Research Inst.) 33 p HC $4.75 CSCL 14C

N74-17161

Unclas
G3/14 30551

IITRI

FEASIBILITY MODEL OF A HIGH RELIABILITY FIVE-YEAR TAPE TRANSPORT

Technical Report - Volume I

IITRI Project No. E6225

Contract No. NAS5-21692

Goddard Space Flight Center
Greenbelt, Maryland

TECHNICAL REPORT - VOLUME I

SUMMARY REPORT FOR FEASIBILITY MODEL OF A HIGH RELIABILITY FIVE-YEAR TAPE TRANSPORT

5 January 1972 - 5 November 1973

Contract No. NAS5-21692

Prepared by

R. L. Eshleman
A. P. Meyers
W. A. Davidson
R. C. Gortowski
M. E. Anderson

Submitted by

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

For

Goddard Space Flight Center
Greenbelt, Maryland

October 1973

FOREWORD

This is the final report on IIT Research Institute Project No. E6225 entitled: "Feasibility Model of a High Reliability Five-Year Tape Transport." The work was performed for the National Aeronautics and Space Administration, Goddard Space Flight Center under Contract No. NAS5-21692. The work was completed over a 21 month period and was monitored by Mr. Carl Powell of GSFC.

The project was divided into two major phases, the first being the design, development and fabrication of the High Reliability Five-Year Tape Transport, and the second being the analytical and experimental evaluation of its performance and reliability.

Results of this program are reported in three separate volumes. These include, Volume I - Summary Report, which provides an overview of the transport development, its performance and test results, and sets forth the conclusions and recommendations. Volume II contains a description of the system design, the analyses performed, and results of the tests performed to determine the transport's performance capability. The third volume contains all appendices and presents the detailed drawings and analytical tools used in the various analyses.

Respectfully submitted,

IIT RESEARCH INSTITUTE

M. E. Anderson
Assistant Director of Research
Electronics Division

Approved by:

Sidney Bass, Director of Research

ABSTRACT

This program was begun by selecting one major design criterion, i.e., that operational life should take priority over any previously determined set of specifications. Simplification of the number of mechanical elements in the system seemed desirable, since multiplication of these elements has contributed to premature failure in a number of spacecraft type transports. A new set of specifications and a transport configuration, both of which were primarily based on long life, had to be identified.

To this end, certain design guidelines were established, and the design strategy of modularization was used. The reliability criteria for the transport system were: minimum mechanical complexity, minimum interacting mechanical functions, conservative use of components, component selection from large volume production, adaptability to modularization, and minimum tape handling stress.

An analytical model of the tape transport was used to optimize its conceptual design. Each of the subsystems was subjected to reliability analyses which included structural integrity, maintenance of system performance within acceptable bounds, and avoidance of fatigue failure. These subsystems were also compared with each other in order to evaluate reliability characteristics. These evaluations were made by using fundamental analytical techniques for the computer simulation of a transport system.

The Five-Year High Reliability Tape Transport described is a transport in which no mechanical couplings are used. Four drive motors, one for each reel and one for each of two capstans, are used in a differential mode. There are two hybrid, spherical, cone tapered-crown rollers for tape guidance. Storage of the magnetic tape is provided by a reel assembly which includes the reel, a reel support structure and bearings, dust seals, and a DC drive motor.

A summary of transport test results on tape guidance, flutter, and skew is provided in this report. The guidance results indicate that a substantial increase in lateral packaging density can be achieved. Improvements in jitter and skew would allow a recorded capacity of 1.4×10^{11} bits to be achieved without major re-design.

The major usefulness of the transport will be as a test-bid applicable to other satellite recorders. To maximize the versatility of the recorder to meet this objective, it is recommended that future developments include: (1) the design and packaging of the electronics to accommodate higher bit capacity, (2) the determination of the guidance capability when 1/2 inch or 2 inch tape is used, and (3) replacement of the drive motors to eliminate tape handling problems due to the use of brushes.

TABLE OF CONTENTS

TABLE OF CONTENTS CONT.

LIST OF FIGURES:

FEASIBILITY MODEL OF A HIGH RELIABILITY FIVE-YEAR TAPE TRANSPORT

1. INTRODUCTION

1.1 Background

Performance limitations of spaceborne magnetic tape transport systems became apparent to the IITRI staff during its study of magnetic head/tape interface problems on satellite tape recorders. During this study, on NASA Contract NAS5-11622, the dependence of system performance on the transport design was recognized to be a significant factor. These observations led to the initiation of Contract No. NAS5-821556, entitled: "Design Study for a High Reliability Five-Year Spacecraft Tape Transport". This nine month program, initiated in mid-FY'71, was followed by the program covered in this report.

1.2 General Philosophy

The main objective of this program was the design and fabrication of a prototype spacecraft tape transport possessing high reliability and long life. In order to achieve this objective, an overall philosophy was established which included a set of program goals which differed from those normally followed in the design of a magnetic tape transport for unattended use in space.

Previously, satellite recorders have been, by necessity, designed to conform to a set of stringent specifications. These specifications not only established performance criteria but also values for power, weight, and volume. Such values were obviously necessary because of payload and power limitations, but they forced the system mechanics to conform to unusually tight limitations. Many successful recorders of this type were produced and it is a tribute to engineering ingenuity that they fulfilled these stringent specifications. Recently, however, greater emphasis has been placed on extending the operational life of such systems and it is here that failures have occurred.

It is not unreasonable to conclude that the heavy burden placed on the mechanical systems in achieving these unusual specifications resulted in their limited operational life. Mechanical failures have been observed in such components as the magnetic tape, belts, bearings, etc. Certain failures, such as an increase in tape flutter or deterioration in guidance, are not always catastrophic but can be related to failures in the mechanical system.

Coupled with the identification of a set of specifications was the need to identify a transport configuration where all considerations were made on the basis of long life. In the past, the need to conform to specific geometric form factors and limited power availability has generated a family of satellite recorders which include novel configurations, such as the negator spring coaxial reel type. Long operating life was not, however, a primary consideration in these machines. Much effort has subsequently been expended in extending the operational life of these and other transport designs. One year operation is possible and two probable, but life beyond two years is considered unproven and probably unobtainable.

It was mandatory, therefore, in considering a high reliability five-year transport design, to identify a transport configuration which was in no way influenced by any factor other than those related to maximizing life. Realistically, tradeoffs between life and even the broad envelope of specifications were bound to occur and, in fact, did.

The philosophy that life shall predominate over all other requirements led to a set of program goals necessary to achieve this prime objective. These goals were:

- The identification of a transport configuration in which all considerations were made on the basis of long life.
- The identification of life limiting aspects of the transport as a whole.
- The identification of a design procedure, using analytical modeling, to maximize life.

2. DESIGN GUIDELINES

In order to achieve these goals and objectives it was necessary to establish a set of rules or guidelines, the use of which would allow trade-off decision-criteria to be consistent throughout the program. These machine System Reliability Guidelines were:

- To recognize the limitations of applying traditional reliability analysis to satellite tape recorders.
- To maximize the use of analytical capabilities relevant to the overall system.
- To ensure adaptability to modularization
- To adhere to minimum mechanical complexity and minimum interactive mechanical functions.
- To select a system and components well within historically proven performance regimes.
- To acquire components from the largest production population possible, therefore attempting to obtain not a unique sample but a statistically average sample.
- To recognize the need to establish realistic life testing techniques throughout the system.

Many of these guidelines are self explanatory, but one or two require a brief explanation. There is a drawback to applying traditional reliability analysis to satellite tape recorders, primarily one of limited knowledge. There is only a small amount of failure rate information available and little or no knowledge on the prognosis relative to life of a running system. A failure in orbit may be due to a multiplicity of causes but the exact cause usually remains unknown or uncertain. Clearly the construction of failure models when information is so sparse is difficult.

The lack of relevant failure information can be attributed to two main reasons. First, the difficulty and therefore the expense of testing and evaluating mechanical systems is prohibitive. This is coupled with the difficulty to successfully duplicate accelerated life tests of mechanical systems in real time. Second and more important is that the accuracy of correlating test data with prediction is questionable. The reliability of mechanical components is related not only to fabrication of the element, but to the installation of that element into the system. The success of a mechanical element such as a belt or bearing in achieving many mission lifetimes on a life test model appears to have little relationship to the failure of an identical element installed in another system. Therefore the ability to generalize test data is very difficult.

What was needed to overcome this severe limitation in mechanical systems for long term unattended use was a radically new approach both in the analytical design stage and in the subsequent life testing, so that a mechanical element could be selected on the basis of its own behavior rather than on the premise that an identical element behaved well in life tests. This approach included one of the techniques used in electronics to eliminate short term failures from long term systems, i.e., the burn-in period. The burn-in period can be productively employed to evaluate long-life mechanisms. To realize this approach required modularization of the transport.

3. MODULARIZATION

Modularization was the key design strategy selected to overcome the insufficiency of failure information connected with products of extremely limited numbers such as satellite tape recorders.

Modularization in this context implies uniting a functional subsystem. Storage of the tape is one example of a function. Its related subsystem is not the reel alone; it is the reel, the bearings, the bearing supports, and the drive system. All of these are designed to form a module which can then be inserted as a unit into the tape transport. The advantages to such a system are many but the prime advantage is associated with a new approach to pre-flight testing to ensure long life.

Modularization of a transport, to be effective, requires fabrication of several modules of the same function. Let us say, for example, that six or eight reel assemblies are fabricated. Each one is then subjected, as a subsystem, to a burn-in period of 10 percent of the total operational life required, in this case, six months. During this burn-in period all the modules are continually evaluated so that a running signature of performance is established for each over a five to six month period. At the end of this multi-month period, one or two modules are then selected on the basis of performance, e.g., drag, torque, acoustic signature, etc. In this way there is some evidence that a module will continue without a major change or serious degradation which would indicate that an early failure is likely to occur.

The set of modules selected would then be assembled into the transport as a whole and qualification testing would begin. While this transport is being qualified as a complete mechanical system, the remainder of the modularized subsystem would continue to be tested as individual units. In this way, at the end of the qualification period all modules would still have an equal life evaluation time and any component degradation may be observed. If component failure occurred during qualification of the assembled transport, the module responsible for the failure could be replaced by an equivalent module that is still performing satisfactorily.

4. RELIABILITY CRITERIA

4.1 Minimum Mechanical Complexity

For the function required, e.g., for multiple speeds, it is essential to transfer speed changing functions from belt-driven complex mechanical transmissions to motor and electric controls.

4.2 Minimum Interacting Mechanical Functions

This criteria emphasizes the need for assuring against serially adding functions, that is, each component is independent from an adjacent failure probability. Minimum interacting mechanical functions were deemed crucial to successfully achieving a sound, uncomplicated mechanical design which has the potential for filtering or impeding incipient failures or their impact on the system.

4.3 Select and Design System Components Well Within Historically Proven Applications and Performance Regimes

This factor focuses upon specific elements within a transport to assure the proper application of mechanical components from the view of function and life. In this study, this implied that use could not be made of a mechanical system that had neither performance experience nor manufacturing quality control history behind it. It was, therefore, essential that the mechanical system have some historical evidence of successful operation in the multi-year area. When components are not chosen in this regime, the effective prediction of life is difficult and there is no operational justification or experimental evidence whatsoever to substantiate long life.

4.4 Component Acquisition from Largest Population Possible

It is essential that a specific configuration not require exotic or limited availability components, since these elements have little or no performance history from which to judge life. Selection from a large population maximize the chances of obtaining average samples whose statistics are known.

4.5 Adaptability to Modularization

To bring a five-year life design through the development and system qualification phases, it is essential to test and evaluate separately subsystems such as capstan modules and reel-to-reel drive subassemblies. Since component run-in and evaluation might require 10% of the mission life, it was anticipated that the testing and qualification cycle would entail the simultaneous testing of several identical models of all transport subsystems. When a subsystem fails during qualification, it is impossible, because of time limitations, to recycle the whole transport. Thus, the modularization strategy permits the failed module to be removed and replaced by a qualified substitute, thereby permitting the transport qualification to progress without a major setback or delay.

4.6 Minimum Tape Handling Stress

For a transport that is expected to produce at least 50,000 tape passes, a critical parameter is tape handling. To minimize tape oriented problems, it is important to reduce to an absolute minimum the mechanically induced stresses. There are two main areas in which high stress levels occur in the magnetic tape system; namely, in the tape pack itself and in the tape handling and guidance. This is an extremely critical area which has been somewhat neglected throughout the industry in the past.

The design configuration was carefully examined during this study for its ability to handle the tape in a manner which minimizes the tape stresses throughout the system. There is little doubt that when the magnetic tape experiences severe stress levels while being handled, premature degradation often follows. To meet the prime objective of a five-year operational life, high stress levels had to be eliminated throughout the tape pack system.

5. ANALYTICAL MODELING

To overcome the severe limitations of a mechanical system for long term unattended use, emphasis was placed on analytical modeling of mechanical systems. The analytical model of the tape transport is an integral portion of the design approach. Use of the model allows optimization of the conceptual design by variation of model parameters. In this way a design can be obtained that requires minimum hardware development.

The design procedure using the analytical model begins with the selection of a concept. This concept was selected on the basis of minimizing the number of critical elements in the system. The analytical model of this concept is used to select dimensions, materials, and components based on long life and performance. The stresses in the various components are compared to their strengths, and the performance of the system is, with typical error sources, compared to that of normal transports. In addition, the degraded (with respect to wear) transport performance is compared to that of the new transport. In this way the performance of the transport after a finite time interval can be assessed.

During the study, each of the main subsystems was designed to maximize the system's mission life reliability. In this context, reliability is meant to encompass:

- Structural integrity in withstanding the shock, vibration, and thermal environment.
- The maintenance of system performance within acceptable bounds, e.g., the tape motion irregularities such as time base error and skew must not exceed a specified limit due to the effects of operational aging.
- The design against catastrophic fatigue failure of elements such as belts and bearings.

Relative to the reliability analyses, the first step involved defining the function of each component in the tape transport system, parameter limits for satisfactory operation, and functional relationships and interaction with other components. The second step consisted of an analysis of all possible failure and degradation modes which would be applicable to individual system components or combinations of components, and an evaluation of design and application factors which could contribute to specific failure modes.

Complete analysis of failure modes requires a quantitative, or at least a qualitative, evaluation of likelihood of occurrence. The information necessary to conduct such an analysis came from engineering design and stress analysis, published reliability handbook data, component and equipment manufacturer data, and specific although limited information on failures in present tape transport systems. Further failure mode evaluation was obtained by means of criticality analysis, where probability of each failure was combined with some measure of its effect on system operation to rank each possible failure according to a criticality index.

Comparison of various subsystems in terms of reliability characteristics was made on the basis of a number of possible failure modes for each system, comparison of effects on performance, and a comparison of failure criticalities of each element. This evaluation also gave an indication of points where redesign, derating, improved quality control and inspection would be most effective in improving reliability. For portions of the tape transport system where varying amounts of failure data were not available, evaluations and comparisons were made on the basis of subsystem reliability analyses based on such data, utilizing standard reliability modeling, and prediction techniques.

In evaluating the long term operating performance, it was essential to simulate the design in dynamic terms. Study was then done on the influence of error source generators, such as bearings and eccentricity in film guiding surfaces. Prediction of the implications of aging effects due to wear and lubricant viscosity variations was made. In these evaluations, use was made of fundamental analytical techniques, developed at IITRI, for the computer simulation of a transport system as affected by error and system parameter variations. This analysis was effective in portraying how certain performance parameters degrade with operational life; and more particularly focused the design on those areas to which system performance was most sensitive.

6. TRANSPORT DESCRIPTION

The Five-Year High Reliability Tape Transport is a reel-to-reel coplanar configuration with independently driven reels and capstans. This coplanar configuration was selected after evaluating other types of tape handling systems. The deck layout of the IITRI concept is shown in Figure 1. The reel spacing allows for up to 1600 ft. of one mil thick tape. The capstan and idler locations were selected to give reasonably large lead-in tape lengths to each of the crowned idlers. Large lead-in lengths were found beneficial to tape guidance.

The layout also provides large wrap angles (165° and 180°) around the two capstans and clearance space for the record head. A straight length of tape for mounting the erase head and a non-contacting end-of-tape sensor is also provided. Furthermore, the oxide tape surface does not contact either crowned idler. This minimizes debris and wear.

The deck occupies an area of approximately 169 inch^2 and the entire transport can easily be packaged in a 13 x 13 x 5 inch volume.

An aluminum mounting deck is used in the construction of the feasibility model. This deck has a thickness of 0.625 inch and is accurately machined to accept the modules.

Storage of the magnetic tape is provided by a reel assembly. The reel assembly is an independent module that includes the reel, a reel support structure and bearings, dust seals, and a DC* drive motor. This compact configuration is obtained by directly attaching the DC motor armature to the reel. The DC motor field housing is an integral part of the module's support housing.

*DC brush/commutated motors were employed because of developmental cost constraints - advanced models may be fitted with DC brushless motors.

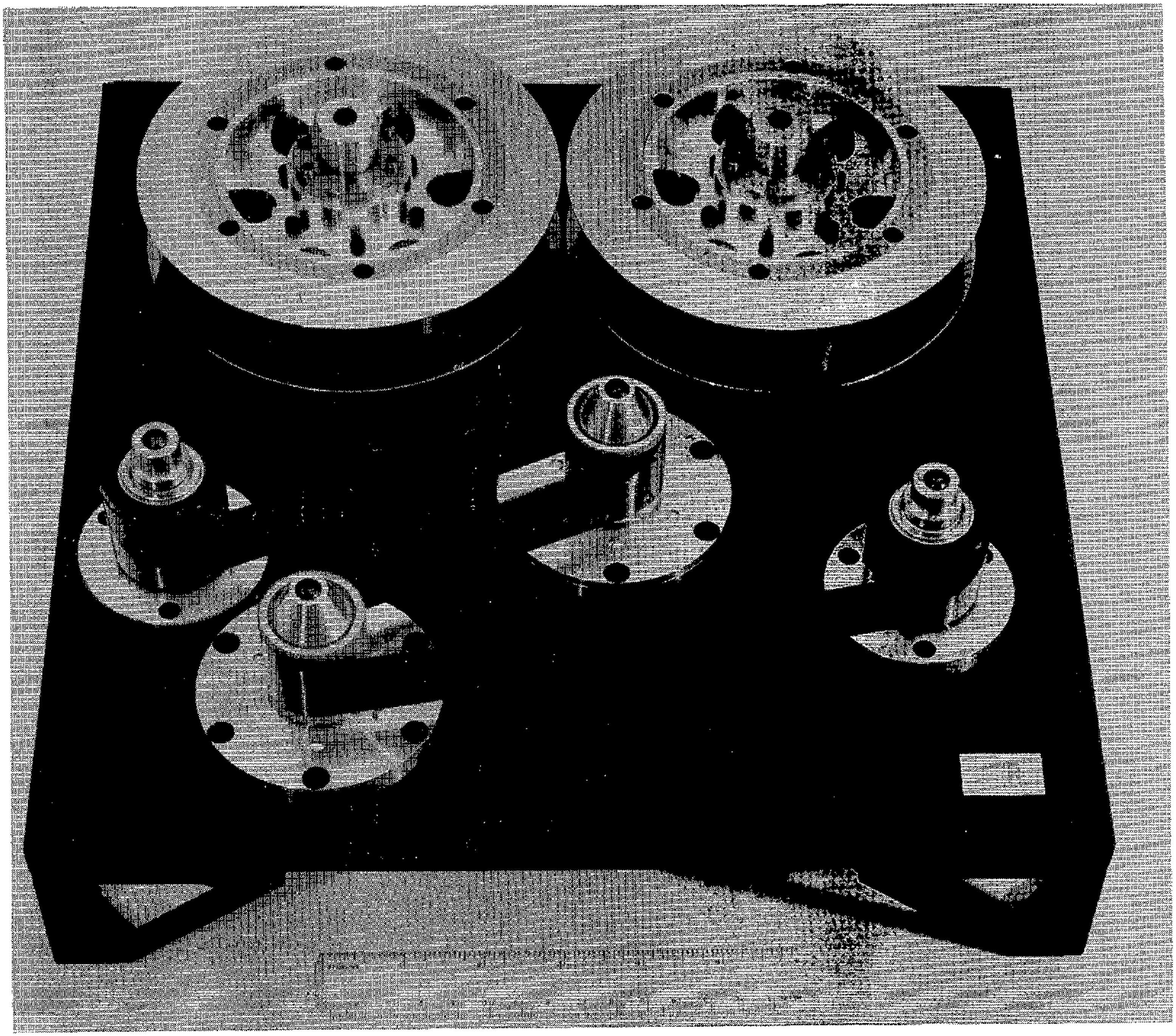

Fig. 1 FIVE YEAR HIGH RELIABILITY TAPE TRANSPORT - DEVELOPED BY IIT RESEARCH

Substantial bearings of the Precision Class are preloaded to a 24 ounce level by using a calibrated preload spring technique. Preloadings are employed to assure effective bearing performance as well as to minimize the runout effects resulting from internal bearing clearances. Reel shaft run-out errors are directly translated into gross tape tracking errors. To minimize these reel generated tracking errors, preloading and precision mechanical assembly procedures are employed to control reel hub run-out to less than ± 0.0005 inches.

The capstan assemblies provide for low and high speed tape metering. Both assemblies utilize direct drive DC motors to control the tape in the vicinity of the head, and to mechanically filter tape propagated disturbances. The DC motors induce damping from the electrical field and help to control tensions through drive or drag (back emf).

Tape guidance is performed by the two double coned idler assemblies. The idler collars are 1.5 inches in diameter and have a 2 degree cone angle. The apex of the roller is rounded with a 3 inch radius. This radius reduces the stress level at the tape centerline but allows the roller to guide as a double cone. The double coned roller rotates around a support post through two precision bearings. The support post is integrally mounted to the idler housing. Prependicularity is achieved by maintaining a close control between the housing and the deck plate surface.

A differential screw mounted to the bottom of the support post allows control of the dynamic equilibrium position of the tape. Additional details and complete drawings of the transport deck and each module are provided in Volumes II and III of this report.

7. TRANSPORT TEST RESULTS SUMMARY

The objective of all tests performed on the Five-Year High Reliability Tape Transport was to evaluate its performance with regard to movement of tape past a record/playback head. Of specific concern was the smoothness with which the tape passed the head, as measured in lateral motion across the head, in skew over the head, and in jitter or flutter representing variations in tape velocity. Performance was measured at different speeds over a range lf 3 to 72 ips and at various positions on the tape including beginning, middle and end of tape. The amount of tape tension required at the head tape interface to achieve high density recording, was evaluated for this transport. Further, the tape tension required to achieve precision guidance during operation over this range of tape speeds and the necessity of closed-loop servo control of both reels and capstans was examined. Results of these tests are summarized in the following sections with greater detail presented in Volume II.

7.1 Tape Guidance

Tape guidance was first observed by measuring the lateral displacement of the tape edge with a Physitech detector and graphic recorder. Substantial motion on the order of 1 to 3 mils was evident for short term variations and 5 to 15 mils was characteristic of long term variations. After a series of tests were performed, it was evident that this displacement was characteristic of the particular length of tape on the machine since its "edge signature" was reproducible on each pass.

Tests were then made by observing the output level of the playback head for the total length of tape. This was accomplished by recording after the tape has reached a quiescent, stable condition; the subsequent playback signal stability showed that the long term lateral variation was within 0.5 mil and the short term variation on the order of 0.32 mil. Comparing the results of these measurements, it is clear that any form of edge guiding would lead to serious mechanical and tape damage problems.

It further has demonstrated that the concept employed on this machine, of providing sufficiently long lead-in tape lengths to the two crowned roller guidance modules, effectively achieves the desired goal of precision tape guidance. With lateral motion limited to 0.5 mil, it is reasonable to increase the lateral track density of the recorder, particularly when considering bi-phase digital recording, to track widths on the order of 2 to 5 mils and spacings on the order of 1 to 3 mils, thus easily achieving the capacity goal set for this recorder.

The guidance tests performed to evaluate the tape tension and the form of tension control required showed that maintaining 6 to 8 ounce tape tension in the area of the head at both high and low speeds was necessary to maintain intimate contact. Also, tape tension in the left reel area had to be maintained at 12 ounces at high speeds, to assure an acceptable, repeatable tape pack. Further, a comparison of the guidance and pack characteristics as a function of closed loop servo-control, as compared to open loop constant torque drive, revealed that while there were slight differences, the closed-loop tension control is not necessary. It became apparent that reel tension can be maintained by programming 5 to 10 torque settings over the full length of tape, thereby eliminating the need for tape-contacting tension sensors.

7.2 Flutter and Skew

Both flutter and skew, as observed at the head tape interface, are induced by variations in the power applied through the drive motors, variations in loading, and eccentricities of all rotating elements of the transport. Further, the tape flutter and skew components can be attributable to the character of the magnetic tape and the consistency of the substrate on which the oxide coating has been applied. The series of tests performed gave insight into the origin of many of the flutter and skew components.

Flutter measurements were made on different channels and all locations of tape from one end to the other. A recording made at 60 ips was used for all measurements. The maximum rms flutter in a band from DC to 5 kHz, with the transport operating at 60 ips, measured at 0.16%. At a playback speed of 30 ips, the flutter increased to 0.20%. At these tape speeds the measurement was essentially consistent over the entire length of tape. When playing back the tape at 3.0 ips, the flutter measured 0.43% in the mid-section of the tape supply with pronounced increases to 0.86% near both ends of the tape.

These measurements were also made in the form of peak amplitude jitter. The results, again based on a bandwidth ranging from DC to 5 kHz, were 0.44% at 60 ips, and 0.56% at 30 ips. At lower playback speeds the peak jitter was twice as great at the ends of the tape as compared to the mid-section. In each case the flutter measured on playback is the combined record/reproduce flutter.

At a transport speed of 60 ips the maximum skew deviation was ± 0.170 mil. Playback of the same recording at 30 ips rendered a somewhat smaller skew measurement of ± 0.115 mils peak-to-peak. Similarly the same recording reproduced at 3 ips rendered a skew of ± 0.10 mils.

A measure of run-out on all four rollers which make contact with the tape revealed inaccuracies approaching 0.5 mil peak-to-peak run-out. It must be noted that precision elements were used in the construction of these modules; however, these were not ground on their bearings, nor were they assembled with specific "balancing procuedures" employed to effectively minimize run-out effects. The "balancing-out" procedure was employed in the assembly of one module, and resulted in demonstrating a reduction in run-out from 0.5 mil to approximately 0.10 mil. It was further noted that run-outs, when measured on inside and outside edges of the capstans tape contact areas, were not "in-phase", thus providing a measure of the amount of wobble which induces skew. It is apparent that these measurements indicate that the skew and flutter can be reduced by "balancing out" inaccuracies in the capstan and crowned roller output figures.

It must be noted, however, that a substantial portion of the jitter measured is induced by the capstan drive motors pulsations. This is especially attributable to DC-brush commutated motors. It is expected that this effect will be reduced by employing brushless DC motors. This effect could be essentially eliminated if AC motors operating at a high slip ratio were used. The penalty would be larger size motors and higher power consumption, due to their inherently lower efficiency.

8. STATUS OF DEVELOPMENT

The design of a tape transport exhibiting exceptional performance characteristics has been successfully demonstrated. This was done through utilization of the design guidelines and the analytical tape transport models. As yet, life and reliability tests have not been exhaustively performed on the tape transport to prove out the estimate made. These estimates, however, are based on experimental test results and, since the transport system is built on a modular basis, it is quite certain that the reliability figures provided can be accepted with substantial confidence.

The five-year high reliability tape transport developed during this program was not packaged in a container, as is customary for satellite flight models, nor were the control electronics packaged to allow for comparison of volume and power requirements with other satellite tape transport systems. The complete transport and control electronics, with associated laboratory equipment used in making many of the measurements and performing the record/playback functions, is shown in Figure 2. The control electronics were designed, and as a matter of fact "over-designed", to allow for variation in parameters of interest and to provide for a comparison of closed-loop and open-loop operation during the tape guidance tests.

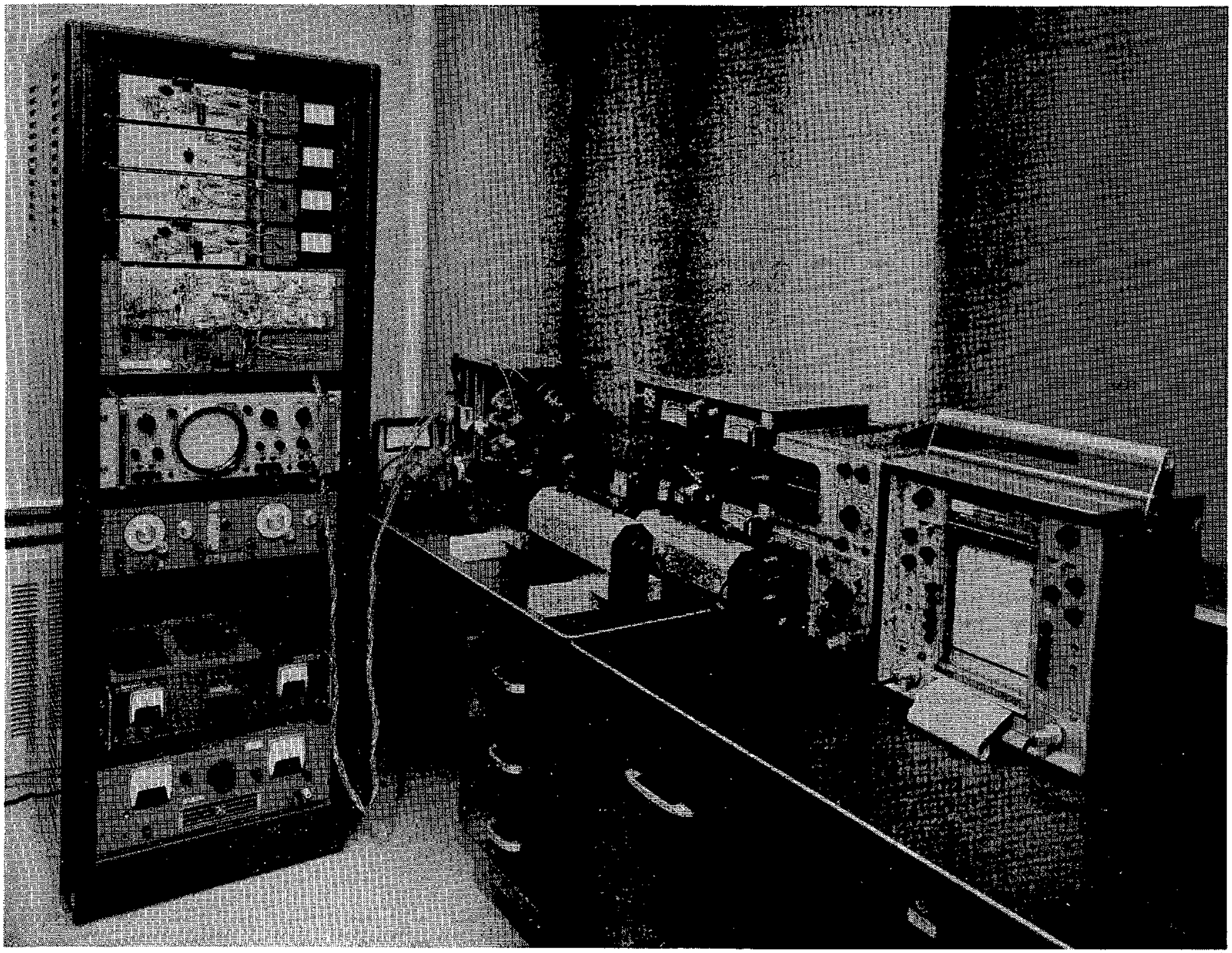

Fig. 2 TRANSPORT UNDER TEST

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Transport Performance

9.1.1 Recommended Controls

Since the tests (see Section 4.3, Vol. II) indicate that both tape guidance and the record/reproduce performance of the head are not critically related to tape tension, there is no need for a precise, closed-loop tension control system and, thus, no need for tension sensors.

Adequate control of tension can be provided with open loop control of each reel motor's torque in such a way that the latter is varied in small steps and made approximately proportional to reel pack radius. High reliability non-contact sensing of tape pack radius for such an open loop control can be provided by a line array of 5 to 10 photodetectors below the tape pack, viewing a light source above the tape pack. As indicated in the tests performed, a tape tension of 6 to 8 ounces appears adequate at the head and supply reel for both 3 ips and 60 ips, but a tension of about 12 ounces is required at the take-up reel to achieve a consistent tape pack.

9.1.2 Guidance

Accuracy and precision of tape guidance achieved with the design of this transport allows a substantial increase in the lateral packing density of tracks for digital recording. The points where guidance can be improved are in minimizing skew and time jitter effects.

It is recommended that additional tests be performed on tape guidance employing different tape samples and different thicknesses. Tape widths of 0.5" could be run on the existing transport to determine the guidance characteristics achievable at this width. It is recommended, in consideration of higher capacity recording systems, that the performance of this transport be evaluated in guiding 2 inch wide tapes. It would also be appropriate to explore the application of double sided tape to this transport. Specifically, it is recommended here to consider the guidance performance capability of this technique using 2 inch wide tape with its oxide side run in contact with the crowned rollers and capstans.

9.1.3 Jitter

Since the torque ripple (due to the finite number of commutator bars) of the reel drive motors is the dominant disturbance giving rise to tape speed flutter (see Section 4.6, Vol. II), it is clear that the flutter performance of the transport could be significantly improved by either eliminating the torque ripple, or isolating the tape in the vicinity of the head from the influence of the reel motor torque ripple. The latter action could be achieved by introducing a low compliance, spring-loaded floating idler in the tape path near each reel. Such an arrangement would offer the additional advantages of isolating the speed-control system from the reel inertias and eliminating the present configuration's strong longitudinal tape resonances in the neighborhood of 14 to 25 c/s. The principal disadvantages of such a floating idler are the additional mechanical complexity and the difficulty of providing low-friction translation of the idler without guidance degradation.

9.1.4 Recorder Capacity

Record capacity is closely coupled to the degree of precision achievable in tape guidance. As indicated in the previous section, recommendations for consideration of the limitations in guidance with respect to tape width and surface characteristics will dictate the ultimate record capacity achievable. This capacity can be maximized by the reduction of flutter and skew. In extrapolating the measured performance of this tape transport, it is reasonable to anticipate an ultimate recorder capacity of over 1.4×10^{11} bits. This is based on achieving 200 tracks across a 2 inch tape which is coated on both sides, is 3,000 feet long, and has a per channel recording density of 10,000 bits per inch. The achievement of these goals, of course, calls for further design, development and testing. Further, it involves the adaptation of finer gapped record/playback heads capable of achieving the higher density.

9.2 Consideration for Adaptation of the Transport to the Satellite Environment

9.2.1 Hardening to Shock and Vibration

Shock and vibration environments associated with satellite launch generally induce significant forces in the tape transport. This factor was taken into consideration in the design and development of this tape transport. The two major problem areas involve the tape and the antifriction bearings.

In the first case, i.e., that of maintaining a tape pack during the high launch accelerations, flanges have been utilized on the tape transport reels. The transport would be mounted in the satellite in such a way as to avoid excessive slip and breakup of the tape pack due to acceleration loading. This would be done by mounting the recorder so that the axes of the transport are perpendicular to the acceleration forces. It is further anticipated that tape tension would be maintained during launch to hold the tape firmly in place against the idlers, capstans and heads. This could possible be done statically by application of electrical power to the reel motors, or by mechanical tensioning devices which would be released when power is applied to the transport.

While the antifriction bearings have been substantially overdesigned with respect to the actual transport loads to provide a substantial safety margin against failure, it may be most appropriate to cycle the recorder during the launch period to preclude any tendency toward bearing race brinelling.

It is recommended that during subsequent phases of transport development, particular attention be paid to loading factors to insure a design which is not degraded during the launch cycle.

9.2.2 Power Requirements

As indicated in Section 4.7 of Volume II, the total power input for the transport, and its associated control systems in the record and playback modes, varies from about 43 to 88 watts, depending almost entirely on the tape tensions selected. Included in these totals are 10.5 watts for relays and lamps, 4.4 watts for voltage regulators, and 3.0 watts for all circuitry loads. The four motors dissipate from 7 to 30 watts, depending on the torques developed, while the four power amplifiers dissipate the remaining 18 to 40 watts.

If reduction of total power consumption were vital, the largest single improvement could be effected by replacing the present dissipative linear class-B power amplifiers with high-efficiency, switching-type class-D power amplifiers (e.g. TRW type MCA 1002). Four such amplifiers probably would have a combined dissipation of about 6 watts when driving the present motors at the maximum required torques. Switching type voltage regulators also could be employed to reduce their combined dissipation to less than a watt. Further power reductions could be made by eliminating the lamps, substituting solid-state switches and more logic for some of the relay functions, and making some circuit modifications.

With all of these changes, the total power consumption probably could be reduced to about 17 to 42 watts, depending on torques. Incorporation of less-efficient brushless motors would raise this power requirement.

9.3 Recommendations for Further Transport Development

Having successfully completed this program with the demonstration of a high reliability long life tape transport designed in accordance with previously established guidelines, it is clear that this concept could be further developed and applied to a range of satellite tape recorder requirements. The recommended task areas for future development are listed below:

- Design and package the control electronics for the existing tape transport, with record and playback electronics associated with a higher density record and playback head, to provide a 7.2×10^9 total bit capacity. Also replace all DC-brush motors with DC-brushless motors and initiate longer term performance tests.

- Perform a series of tests with the existing unit to determine the guidance characteristics when employing 1/2 inch tape.

- Modify the guidance modules to allow evaluation of the guidance capability of the system in order to accommodate 2 inch wide tape by using the same drive motors and electronics, but with half the tape length to match generally the reel inertial characteristics. Consider guidance with the oxide side in contact with the crowned rollers and capstans to simulate the situation of employing double sided tape for maximum capacity.

- Explore all factors involved in achieving a data capacity of 10^{10} and 10^{11} bits.
  - Maximum tape handling capacity.
  - Maximum lateral channel density.
  - Maximum lineal record playback pulsed density.
  - Minimum tape thickness which can be successfully handled by the transport.
  - Optimization of a tape coating with respect to bi-phase recording of high density digital information.

Finally, it can be concluded that the Five-Year High Reliability Tape Transport development was successful. It has demonstrated the applicability of the design guidelines and analytical models developed for the design of an advanced high performance satellite recording system. Further, the analytical tools and guidelines have been effectively employed on other NASA/GSFC related programs in the evaluation of existing tape transport system characteristics and identification of their shortcomings. IITRI feels confident that future applications of these guidelines and use of the computer models will further substantiate their usefulness.